EVOLUTION OF MID-CHANNEL BARS IN A BRAIDED RIVER AND COMPLEX RESPONSE TO RESERVOIR CONSTRUCTION: AN EXAMPLE FROM THE MIDDLE HANJIANG RIVER, CHINA

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ABSTRACT

Using the middle Hanjiang River as an example, this paper deals with the development of mid-channel bars in a braided river, as controlled by channel boundary conditions, runoff and sediment load, as well as reservoir construction. Relations have been established between indices describing the mid-channel bars and the controlling variables, such as the channel width, the percentage silt-clay content in the channel boundary and the energy expenditure of flowing water. Bank erosion exerts a marked influence on the development of mid-channel bars after reservoir construction. Bank erosion provides space and material for mid-channel bar formation, so bank erosion rate can be closely related to mid-channel bar indices. The middle channel bars exhibit a complex evolutionary response to the reservoir-regulated hydrological regime in the middle Hanjiang River. A descriptive model showing the complex response has been established. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

As a widely distributed channel pattern, braided rivers form important topics of study for many scientists (Bristow and Best, 1993; Best and Bristow, 1993). Recently, progress has been made in understanding the braiding mechanism (for example, Ashmore, 1991; Ferguson and Werritty, 1983; Carson, 1984; Fujita, 1989). Also, measurements and analyses have been made in large natural rivers such as the Brahmaputra River, based on which the evolutionary behaviour of braided rivers has been studied, especially the planform as controlled by bank erosion rate (for example, Thorne *et al*., 1993). Laboratory studies have been conducted in which some interesting phenomena have been observed at the microscale. However, most of the research is focused on certain parts of the braided channel, such as curved segments joined by zones of flow divergence (diffluence) or convergence (confluence) (Bridge, 1993). Little attention has been paid to the overall distribution and evolution of mid-channel bars in relation to influencing factors and the response of bars to an altered system input. In the present study, an effort is made to deal with mid-channel bar development in a large river from a macroscopic viewpoint, using the middle Hanjiang River as an example.

A braided channel pattern is usually characterized by a wide and shallow channel divided by many unstable mid-channel bars. Owing to the rapid and frequent shift of the thalweg, mid-channel bars cannot remain stable. Instead they constantly form, disappear, form again and disappear again. Furthermore, the characteristics of mid-channel bars vary with the changing water stage: during low flow seasons, mid-channel bars appear, and during floods, many may be submerged. Initially the behaviour of mid-channel bars in a braided river seems to be highly random. However, if the long-term long-reach average at a given frequency of discharge is considered, mid-channel bars may show some stable statistical characteristics, and a marked variation is observed between different braided rivers. This makes it possible to study the behaviour of mid-channel bars statistically, to reveal the regularity of how the bars vary in time and space, to establish the relationship of bar development to the influencing factors such as runoff, sediment load and boundary conditions, and finally, to predict the response of bar evolution after the input to the fluvial system has been altered. The issue of mid-

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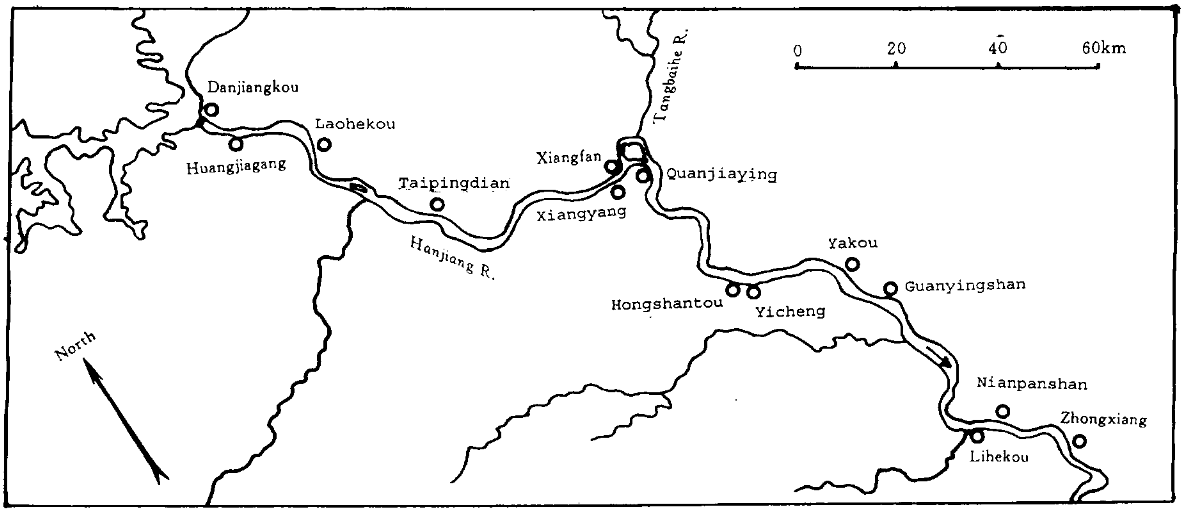

Figure 1. Location of study area.

Table I. Runoff and sediment characteristics in the middle Hanjiang River

Station	Mean annual discharge ($m^3 s^{-1}$)	Mean annual suspended concentration ($mg l^{-1}$)		Suspended load median size (mm)	
		Pre-dam	Post-dam: water storage period	Pre-dam	Post-dam: water storage period
Huangjiagang	1310	3240	36·7	0·010	0·003–0·140
Nianpanshan	1570	2540	679	0·012–0·020	0·026–0·078

channel bar development and evolution is important not only in theory, but also in hydraulic engineering practice, especially in navigation channel training and the maintenance in braided rivers.

The Hanjiang River, 1567 km in length, is the longest tributary of the Yangtze (Changjiang) River. The middle reaches of the Hanjiang from Danjiangkou to Zhongxiang (Figure 1) are characterized by a typical braided channel pattern. The Danjiangkou Reservoir was built in 1959. From 1959 to 1967, the reservoir was used for flood retention, and sediment could be released through the dam. Since then, the reservoir has been used for water storage, with 95 per cent or more sediment intercepted. The hydrological characteristics of this river are listed in Table I. The middle Hanjiang River has a wide, shallow channel, with a width–depth ratio ranging from 210 to 237, and many unstable mid-channel bars which are well developed. After the construction of the Danjiangkou Reservoir, a dramatic change occurred in the input regime of water and sediment in the middle Hanjiang River, leading to significant changes in mid-channel bars. Xiang (1987) has made a study of the mid-channel bar characteristics of the Hanjiang River, with many measurements completed on the 1:10 000 scale topographical maps. In the present paper, the evolution of mid-channel bars will be related to the controlling factors, and the reservoir-induced complex response phenomenon of the evolution of mid-channel bars observed from the middle Hanjiang River will be discussed.

QUANTITATIVE INDICES DESCRIBING MID-CHANNEL BARS

Several indices have been suggested to describe mid-channel bars, among which the most famous is the braiding index proposed by Brice (1964). The braiding index (BI) is defined as twice the total length of all mid-channel bars divided by the length of the central line of the reach. Sometimes the ratio of the sum of the length of all channels to the length of the central line of the reach is also used as an index; it is called the braiding coefficient.

In addition to the above, the following indices have been introduced to express the mid-channel bars in this study:

1. The number of mid-channel bars per unit river length, N (in km^{-1}). When making a comparison between rivers of different dimensions, the dimensionless index Nw may be used, where w is channel width, meaning the average number of mid-channel bars over a length of one width.
2. The ratio of total area of all mid-channel bars (A_b) in a given reach to the channel area (A_r), A_b/A_r.
3. The sum of width of all mid-channel bars at a cross-section (w_{bar}) divided by the bank-to-bank width (w_c), w_{bar}/w_c; for a reach, the average of w_{bar} values at all cross-sections with a regular interval may be used.

The values of the indices used in this study were measured on the 1:10 000 scale channel topographical maps made in different periods. These maps were not made from air photos but were surveyed in the field by the Channel Surveying and Mapping Team, Danjiangkou General Hydrological Station, the Yangtze River Basin Water Conservancy Commission. It should be pointed out that, since the channel of the middle Hanjiang River is unstable with frequently shifting mid-channel bars, caution should be taken in comparison between maps in different periods. However, after reservoir construction, the water and sediment regime was altered greatly, with a pronounced response in the mid-channel bars. So, a trend can be expected in the random variations, and it is not difficult to discern this from large-scale maps. Many details, including small-scale bars, cannot be shown on the map owing to the limitations of survey accuracy and map integration. However, the Hanjiang is a large river with a channel width of about 1000 m, and all major bars can be shown on a 1:10 000 map. The comparison using large-scale maps to identify the macroscopic tendency of mid-channel bar changes can be considered as feasible and reliable. In this study, the 130 km reach from Xiangfan to Lihekou was taken for measuring bar characteristics, and the maps of 1960, 1968, 1978 and 1984 were used. To study the spatial variation in mid-channel bar characteristics, this reach was divided into sub-reaches, and all the mid-channel bar indices were measured. Based on these measurements, a series of relations were plotted, which will be discussed later. The 1960 map was used to represent the pre-dam period. The discharge when the map was surveyed was 1300–1600 $m^3 s^{-1}$, roughly equal to the mean annual discharge. In the post-dam period, owing to the regulation by the reservoir, water discharge below the dam became rather uniform, and the stage related to the channel topographical maps of 1968, 1978 and 1984 approximately corresponded to the mean annual discharge, 1400–1500 $m^3 s^{-1}$. Therefore, the magnitudes of water discharge related to all the maps are comparable, and using these measurements comparison can be reasonably made to show the evolution of mid-channel bars in different periods.

THE DEVELOPMENT OF MID-CHANNEL BARS CONTROLLED BY CHANNEL BOUNDARY CONDITION

From Danjiangkou, the Hanjiang River leaves the mountainous region, runs into a wide-valley plain which is located in a geologically subsiding area, and forms its channel in alluvium. The geological setting of long-term continuous subsidence can be considered as one of the important controls for the formation of the braided channel pattern of this river.

The middle Hanjiang River valley is controlled by the Danjiang Fault Subsidence and the Hanjiang Depression, and from Xiangfan to Zhongxiang the river runs in a graben. This tectonic environment is favourable to sediment deposition. Owing to the relatively coarse sediment load from the upper mountainous region, the channel boundary material of the middle Hanjiang River contains a low content of cohesive material. The median size of bed material in the middle Hanjiang River was 0·148–0·255 mm before reservoir construction, and the bed silt-clay content ranged from 3·5 to 10·6 per cent. The silt-clay content of bank material is also low, generally ranging from 4 to 30 per cent, except where the bank is a terrace consisting of red clay. Also, the tectonically subsiding environment is conducive to lateral erosion and channel widening, a factor which assists mid-channel bar development and channel braiding.

The range of tectonic subsidence exhibits some downstream differentiation, the subsidence in some reaches being greater than in the adjacent reaches. Thus a reach with less subsidence than neighbouring downstream and upstream reaches may be considered as undergoing relative uplift. The thickness of alluvium determined

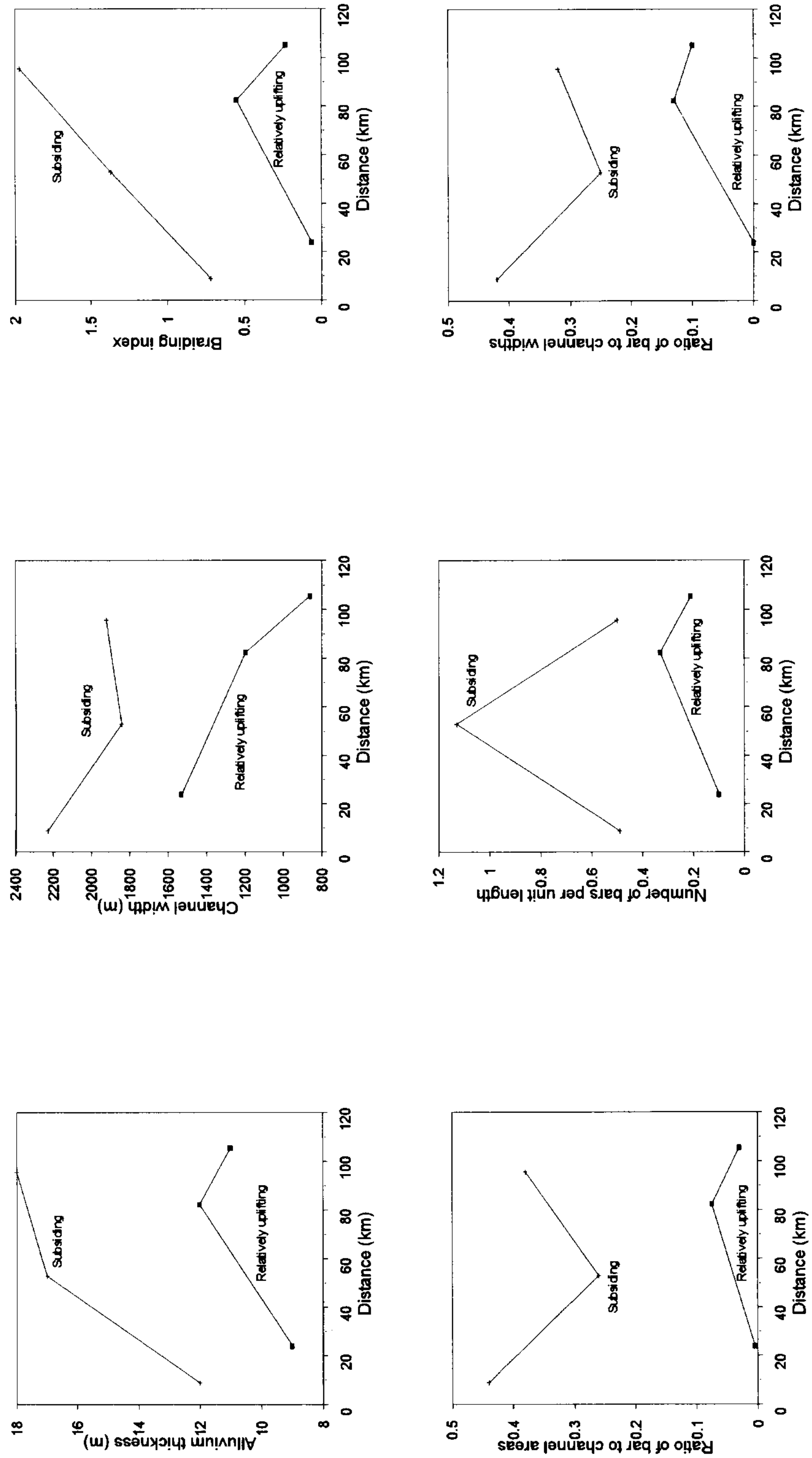

Figure 2. Spatial variation in alluvial thickness, bankfull width, braiding index, ratio of bar to channel areas, number of mid-channel bars per unit length, and ratio of bar to channel widths, showing the influence of the tectonic factor.

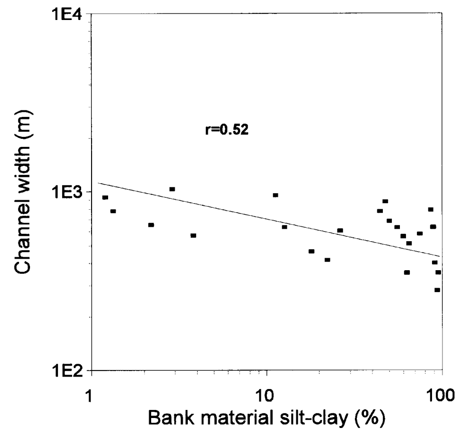

Figure 3. Relation of bankfull width to bank material silt-clay percentage.

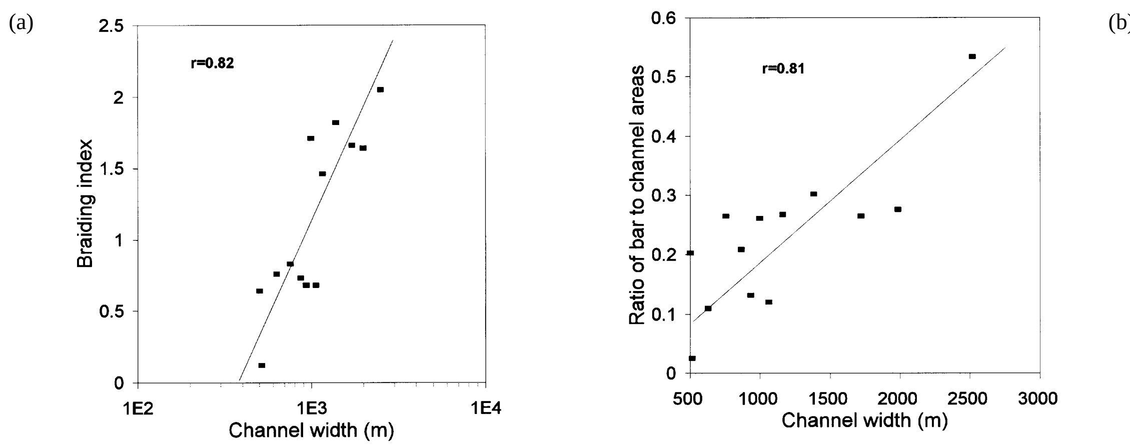

Figure 4. Plots of braiding index (a) and ratio of bar to channel areas (b) against bankfull width.

from bore-hole records can be used to reflect the range of subsidence. Based on this, the Xiangfan–Lihekou reach was divided into six alternately subsiding and relatively uplifting reaches, namely, the Taipingdian–Quanjiaying subsiding reach (only part of this reach is below Xiangfan), the relatively uplifting Quanjiaying reach, the subsiding Quanjiaying–Guanyingshan reach, the relatively uplifting Guanyingshan reach, the subsiding Guanyingshan–Nianpanshan reach, and the relatively uplifting Nianpanshan reach. Based on data from these reaches, the downstream variations in alluvial thickness, channel width and mid-channel bar characteristic indices, BI, N, A_b/A_r and w_{bar}/w_c, were plotted (Figure 2). This figure shows that all values of variables in reaches with relative uplift are smaller than those of the neighbouring subsiding reaches.

Figure 2 shows that channel width can be regarded as a reflection of channel boundary conditions, for example tectonic control, because the channel width in relatively uplifting reaches is systematically larger than that in subsiding reaches. It is well established that channel width–depth ratio is closely related to the weighted silt-clay percentage in the channel's wetted perimeter (Schumm, 1960). Also, channel width is influenced by bank material, as shown in Figure 3, where the plot of bankfull width against the silt-clay content in bank material, based on data from the middle Hanjiang River, indicates a mild negative correlation. Through the channel width, boundary conditions exert a strong control on the mid-channel bar development.

In Figure 4, the mid-channel bar indices BI and A_b/A_r are plotted against the bankfull width w_b, showing that the wider the channel, the higher the degree to which mid-channel bars are developed. This is because, given the

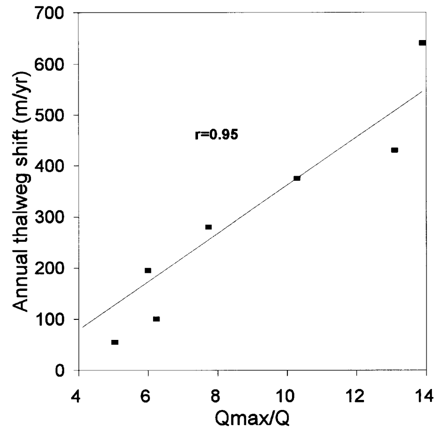

Figure 5. Mean annual thalweg shift as influenced by Q_{max}/Q based on data from the middle and lower Hanjiang River before the construction of Danjiangkou Reservoir.

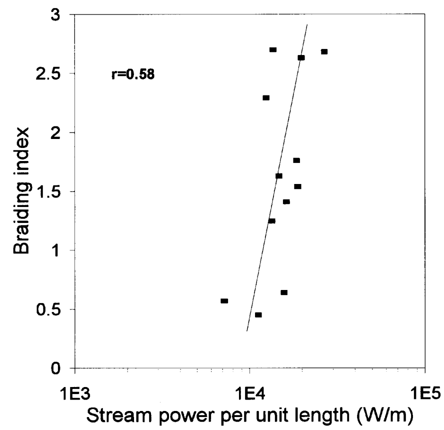

Figure 6. Plot of braiding index against stream power, γQs, based on data from the Xiangfan–Zhongxiang reach.

discharge, sediment is more liable to be laid down in a wide channel than in a narrow channel. From this figure, it can be seen that there seems to be a critical channel width of 400–500 m, above which the channel braids.

WATER DISCHARGE AND SEDIMENT LOAD IN RELATION TO THE DEVELOPMENT OF MID-CHANNEL BARS

Before the construction of the Dajiangkou Reservoir, the mean annual suspended sediment concentration, c, in the middle Hanjiang River was 3240–2540 mg l^{-1}, the coefficient of variation of annual maximum discharge, C_{vf}, was 0·67 at Huangjiagang station, and the seasonal variation of water discharge defined as the mean annual maximum daily discharge divided by mean annual discharge, Q_{max}/Q, was 12·92 at the same station. The water and sediment condition, characterized by a relatively high c, a high C_{vf} and a high Q_{max}/Q, are favourable to the formation of a braided channel and unstable mid-channel bars associated with a rather wide and shallow channel. A high sediment concentration means abundant material available for mid-channel bar formation, and the large seasonal and inter-annual variations in discharge lead to a frequently shifting thalweg (Figure 5).

The middle Hanjiang River has a relatively high stream power expressed by γQs, where γ is specific weight of water, Q the mean annual flood and s the slope, a factor which can be related to the formation of unstable mid-channel bars. The braiding index (BI) is plotted against the stream power based on data from different sub-reaches of the reach Xiangfan–Lihekou, indicating a direct correlation (Figure 6). This figure is based on data

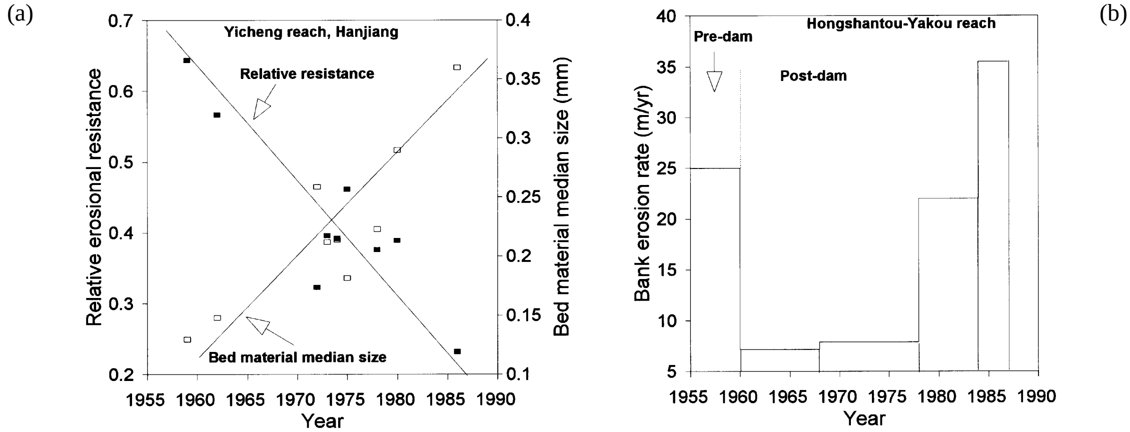

Figure 7. Temporal variation in (a) bed material median size and relative erosional resistance of bank to bed materials, and (b) bank erosion rate.

from the same river, and the discharge is almost the same, so it is the slope that determines the difference in stream power. The fact that the greater the stream power, the higher the BI value reflects that a braided condition represents a higher flow resistance than a hydraulically equivalent non-braided condition. The mid-channel bars represent material which cannot be moved on. As a result of sediment deposition, the channel steepens until a configuration is reached in which the sediment is moved on. This is the inner mechanism of Figure 6.

BANK EROSION IN RELATION TO MID-CHANNEL BAR DEVELOPMENT

Before the construction of the Danjiangkou Reservoir, the bank erosion rate (defined as the mean annual retreat of bank by bank erosion) on the middle Hanjiang River was relatively high, ranging from 20 to 25 m/year (Xu and Shi, 1992). After reservoir construction, as a result of scour by clear water, channel adjustment downstream of the reservoir was dominated by downcutting, leading to a decline in bank erosion. However, with the coarsening of the bed material (Figure 7), the erosional resistance of the bed increased. In the meantime, bank erosional resistance decreased owing to the lower height of newly formed pointbars and their coarser textural composition compared with those in the pre-dam period (Xu, 1989). Thus, the relative erosional resistance of bank to bed material declined, a factor which enhanced bank erosion. Consequently, channel widening occurred and became the dominant feature of channel change. This is confirmed by data from the middle Hanjiang River. The ratio of the critical shear stress of the bank material to that of the bed material, $\tau cw/\tau cb$, has been proposed to express the relative erosional resistance of bank to bed materials (Xu and Shi, 1992). The calculation of τcw and τcb is based on a formula for incipient critical shear stress of both non-cohesive and cohesive materials proposed by Tang (1963). Because the bank material contains a considerable proportion of cohesive fines, and the bed material may be treated as non-cohesive, Tang's formula is chosen to calculate the values of $\tau cw/\tau cb$. The temporal variations in bed material median size, $\tau cw/\tau cb$, and bank erosion rate, R_{be}, are plotted in Figure 7, which supports this reasoning.

This study also indicates a close relationship between bank erosion and mid-channel bar development. Based on data from the Xiangfan–Lihekou reach in the period 1960–1968, Figure 8 gives the plots of BI and N against bank erosion rate, R_{be}. Although the points are scattered, the direct correlation between these variables is clear.

An early study has shown that sediment from bank erosion formed the major part of the sediment load of the middle Hanjiang River after reservoir construction (Xu and Shi, 1992). Because of the reduced flow variability and a gentler slope, the river's sediment-carrying capacity became much lower. When the water flow was incapable of carrying all the material supplied by bank erosion, the coarser part was deposited, forming an initial mid-channel bar. Figure 9 shows a direct relation between the increment of total area of mid-channel bars and the bank area eroded during 1960–1968 based on measurements from the 1:10 000 channel topographical

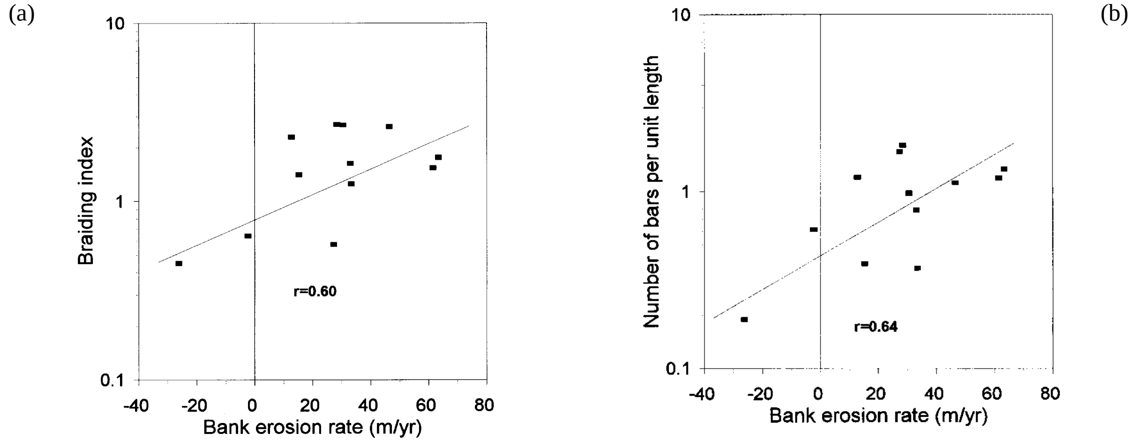

Figure 8. Plots of braiding index (a) and number of mid-channel bars per unit length (b) against bank erosion rate. Negative values mean bank deposition rather than erosion.

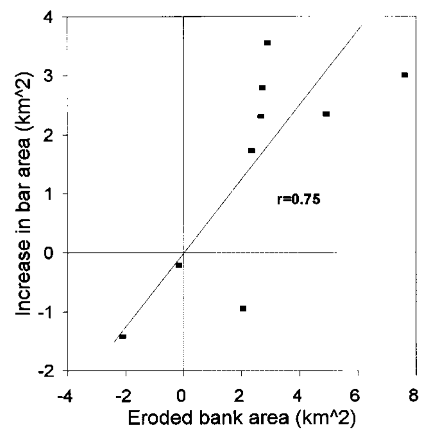

Figure 9. Plot of the increased mid-channel bar area against the eroded bank area. Negative values mean bank deposition.

maps of 1960 and 1968, indicating that the mid-channel bars are more likely to appear where bank erosion is strong. Because part of the sediment produced by bank erosion may be deposited in the sub-reach downstream, the correlation is not high.

The close relation between mid-channel bars and bank erosion is further supported by the identification of source material by mineral analysis. For the reach Xiangfan–Lihekou, the possible material sources for mid-channel bar formation are: (i) sediment from the upper trunk stream of the Hanjiang; (ii) sediment from the largest tributary of the middle and lower Hanjiang, the Tangbaihe River; (iii) sediment from bank erosion. Samples have been taken from the three possible material sources and 20 kinds of minerals and their contents have been identified in the laboratory analysis. To determine how closely the mid-channel bar material is related to the three possible sources, the content of each mineral in the bars is plotted against the content of the corresponding minerals from the upper trunk stream (Figure 10a), the major tributary (Figure 10b) and the river bank (Figure 10c). The three graphs show clearly that the mineral content of the bars correlates most closely to that in the bank, with a correlation coefficient of 0·94; the lowest correlation is to sediment from the trunk stream, with a correlation coefficient of 0·51, and the correlation coefficient between the mid-channel bars and the sediment from the Tangbaihe River is 0·89. Thus the eroded bank material is the major material source for the mid-channel bar formation. Straight lines representing equal mineral percentage in bars and in the material sources are given in Figures 10a–c for comparison. In theory, if the sediment in the bars comes entirely from a certain source, then all points would appear just on the line. If some material is from other sources, the point will

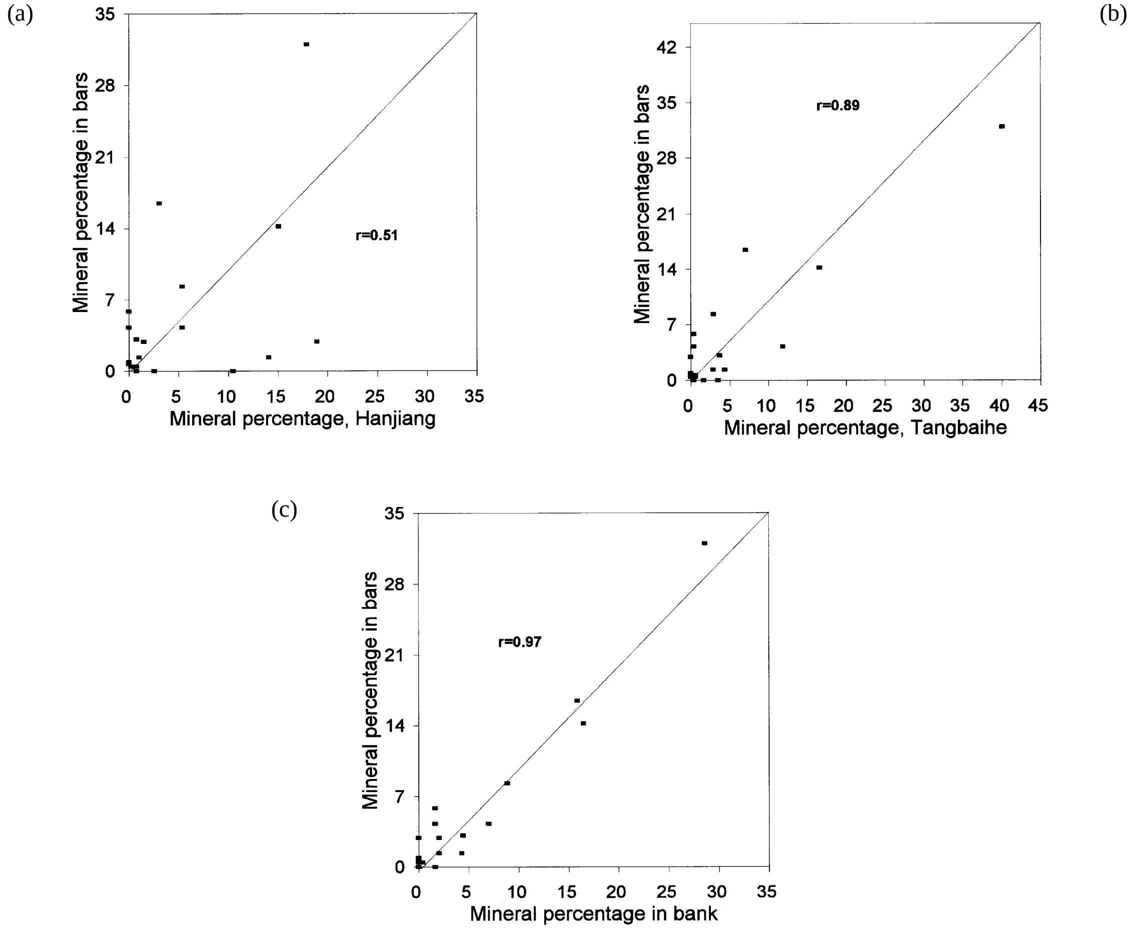

Figure 10. Plots of the corresponding mineral contents in mid-channel bars against those in (a) the upper trunk stream of Hanjiang, (b) the Tangbaihe River and (c) the river bank.

deviate from the line. The greater the deviation, the more material from other sources. Therefore, the following index can be used to determine the degree of importance of each material source:

$$I=\sum(M_{s,i}-M_{bar,i})^2$$

where $M_{bar,i}$ is the percentage of the ith mineral in bars, and $M_{s,i}$ the percentage of the same mineral in a certain material source. M_s may refer to the bank, tributaries or the trunk stream. The smaller the I value, the larger the contribution of the material source to mid-channel bar formation. The I values are calculated for the bank, the Tangbaihe River and the Hanjiang trunk stream as 73·83, 336·37 and 984·58, respectively, showing a marked difference and indicating that the bank material is the major source for mid-channel bar formation.

COMPLEX RESPONSE OF MID-CHANNEL BAR EVOLUTION AFTER RESERVOIR CONSTRUCTION

The phenomenon of complex response in a system can be regarded as a complex adjustment process induced by the time-lag and feedback among different components of the system after the input conditions are altered. In the early 1970s, Schumm (1973) first used the concept of complex response to study geomorphic histories and successfully explained the phenomenon that two levels of terraces can be made by the lowering of base level only once. Xu (1989, 1990) applied this concept to study the channel adjustment induced by reservoirs.

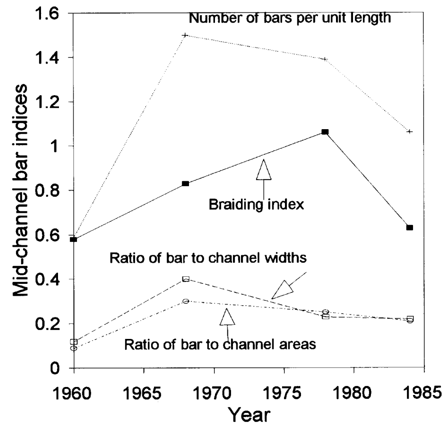

Figure 11. Temporal variation in the values of mid-channel bar indices.

Table II. The decline (–) or rise (+) of water stage at a discharge of 1500 $m^3 s^{-1}$ for different gauging stations (in metres)

Station	Period of flood retention (post-dam)	Period of water storage (post-dam)		Total (1960–1988)
		1968–1977	1978–1988	
Huangjiagang	–1·75	–0·15	0	–1·90
Xiangyang	–0·34	–0·35	–0·56	–1·25
Nianpanshan	+0·11	–0·46	–0·49	–0·84

Mid-channel bars evolve in different ways in river reaches at different distances from the dam. For a given river reach, the temporal variation in mid-channel bar characteristics is often complicated, with different tendencies at different stages of adjustment. Figure 11 shows the variation of mid-channel bar indices over time after the reservoir construction, based on data from the Xiangfan–Lihekou reach. All these indices first increase and then decrease after reaching a maximum. This can be regarded as a complex response in the adjustment of mid-channel bars.

Generally speaking, after a reservoir is constructed on a heavily sediment-laden river, the channel downstream of the dam can be divided into three reaches in a downstream direction, namely, the scour reach, the reach with alternated scour and fill, and the fill reach. As bed scour progresses downstream, the dividing points of these three reaches also migrate gradually in the same direction. Table II gives the decline in water stage at a discharge of 1500 $m^3 s^{-1}$ for different gauging stations. At Huangjiagang station, rapid scour occurred even in the period when the reservoir was used for flood retention; in the early period when the reservoir was used for water storage, the scour became very slow and then the channel became quite stable, meaning that the longitudinal equilibrium was re-established. At Xiangyang station, the bed was scoured continuously, but the scour rate in the period when the reservoir was used for flood retention was relatively slow, becoming more rapid in the period when the reservoir was used for water storage. At Nianpanshan station, the bed was raised by sedimentation in the period when the reservoir was used for flood retention, and then lowered by scour in the period when the reservoir was used for water storage. Therefore, it can be concluded that, in the flood retention period, the Huangjiagang–Xiangyang reach was a scour reach and the Xiangyang–Nianpanshan reach was an alternated scour and fill reach, but with fill dominating; after the water storage period started, the Xiangyang–Nianpanshan reach gradually became a scour reach.

Bar evolution in the scour reach

The channel adjustment of the scour reach is simple, characterized by a continuing decline in the mid-channel bar indices. Consider the example of the Shenjiawan–Laohekou reach, the central point of which is 19 km downstream from the dam. The number of mid-channel bars per unit length in 1960, 1967 and 1977 was 0·59, 0·43 and 0·07, respectively, showing a sharp decline, especially after the reservoir was used for water

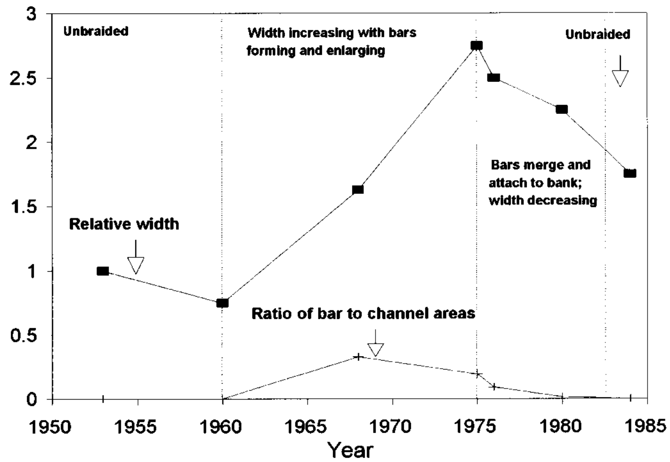

Figure 12. Temporal variation in relative channel width and ratio of bar to channel areas in the Liushuigou reach of Hanjiang River (after Xu, 1989).

storage. Comparison of channel maps indicates that the mid-channel bars merged, enlarged and finally attached to the bank, thus the original multi-braided channel became a single one. This occurred due to a reduction in the sediment-carrying capacity of the river. After reservoir construction, the degree of braiding decreased as the flow of the river was reduced. The sediment-carrying capacity was thus reduced. Second, since water discharge has been largely regulated, the rate of scour was different between major and minor braids. Usually the rate of the former is higher than that of the latter, encouraging the elimination of the minor braids. Third, the hydrodynamic axis becomes fixed in the major braid. Where bank controls exist, the hydrodynamic axis may alternate between the major and minor braids from the high water to low water seasons in the pre-dam period. Thus fill and scour can occur alternately in these two channels, and the mid-channel bar in between may become an island and remain stable for a long time. After reservoir construction, this process can no longer operate owing to reduced flow variation. The minor channel would not then remain stable. Fourth, due to coarsened bed material in the post-dam period, the sand waves became larger. The transportation of bed load often occurs in the form of large sand waves, and when they enter a minor braid and stop moving, the braid is blocked (Xu, 1989).

Bar evolution in the alternating scour and fill reach

The changes in this kind of reach are much more complicated, as shown in Figure 11. The increase in the degree of mid-channel bar development during 1960–1968 was related only to the fact that in this period the reach was alternating between scour and fill, with the latter dominating. The decrease in the values of the mid-channel bar indices after 1968 is consistent with the fact that channel scour has dominated since then.

Coarse sediment from the upstream scour reach may be deposited in the neighbouring alternating scour and fill reach, providing material for the building of mid-channel bars. The gradually enhanced bank erosion in the alternating scour and fill reach also supplies much sediment, which is incorporated into mid-channel bars after an exchange with the sediment in motion. Furthermore, the increase in channel width provides space for new mid-channel bars. All these may lead to an increase in the number and area of mid-channel bars in the alternating scour and fill reach. However, as the point with the strongest scour moves downstream, the alternating scour and fill reach may become a scour reach, and then an inverse change takes place. The process occurring in the scour reach described above now occurs in this reach, giving rise to a rapid decline in mid-channel bar indices. This is why the BI and A_b/A_r values decline after 1968. Additionally, the change of the use of the reservoir in 1968 from flood retention to water storage is also responsible for this. With water storage, the reservoir intercepts about 95 per cent of sediment from the river basin above the dam, thus reducing the sediment available for mid-channel bar development.

In an originally single-thread channel in the alternating scour and fill reach, a more complicated response to channel adjustment has been observed. The adjustment may undergo the following five stages: (1) single-thread channel in pre-dam period; (2) braided and mid-channel bar forming; (3) mid-channel bar enlarging; (4) small bars merging into a big bar and then becoming attached to the bank; and (5) a single-thread channel again. For the Liushuigou reach, the temporal variation in the relative channel width (defined as the ratio of the width in a given year to that in 1954), B_r, and the ratio of the total area of mid-channel bars to the channel area, A_b/A_r, are plotted in Figure 12. It can be seen that before the construction of the reservoir, the reach was a single-thread one, with an A_b/A_r value of 0. After construction of the reservoir, channel width increased and became braided. The highest degree of braiding was reached in 1968, when the mid-channel bar area was one-third of the channel area. Afterwards, with enhanced scour in this reach, the channel became narrower, and the area of mid-channel bars decreased. This is caused by the processes of braid abandonment and of mid-channel bars becoming attached to the bank. By 1984, the A_b/A_r value decreased to 0 and the channel became a single-thread one again.

It should be pointed out that the foregoing model of complex response is an idealized one. The random variation in hydrological variables, for instance the occurrence of a rare flood, may disturb the course of complex response to a greater or lesser extent. However, owing to the regulation of runoff by the reservoir, the intensity of random perturbation is smaller than before reservoir construction, so the complex response process can still be discerned. Even after a strong perturbation by a large flood, the complex response process may be restored and progress in the previously established direction.

CONCLUSIONS

Using the middle Hanjiang River as an example, this paper deals with the evolution of mid-channel bars in a braided channel. The results obtained show that the characteristics of mid-channel bars can be related to factors such as channel boundary conditions and energy expenditure, and are also influenced by bank erosion. After reservoir construction, the changing characteristics of mid-channel bars are significantly related to river bank erosion, because the bank erosion provides both space and material for the building of mid-channel bars. Thus the evolution of bars is controlled to a large extent by bank erosion.

After reservoir construction, the evolution of mid-channel bars in the scour reach is monotonic, and is characterized by a continuing decline in the degree of mid-channel bar development, leading to a single-thread channel. The evolution of mid-channel bars in the alternating scour and fill reach exhibits a complex response, with an increase in mid-channel bar indices in the early stage followed by a decline after reaching the maximum. For reaches which were single-thread in the pre-dam period, a five-stage descriptive model is proposed, generalized as: (1) single-thread; (2) braiding and mid-channel bars forming; (3) mid-channel bars enlarging; (4) small bars merging and then becoming attached to the bank; and (5) single-thread again.

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